Massively parallel computing of 3-D prestack depth migration using phase-screen propagators

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Summary

We designed and implemented an algorithm on the T3D Massively Parallel Processors (MPP) to demonstrate the efficiency of the phase-screen migration method by migrating common-shot gathers in 3-D heterogeneous media. The algorithm was designed to accommodate the hardware architecture on the T3D MPP system. All macroarchitecture characteristics of the MPP system have been taken into account to maintain the MPP, minimize the communication overhead and maximize the sustained computational speed.

A variety of optimizations has been applied to reduce the processing time while retaining a high degree of accuracy of migrated results. The performance and timing of processing on a set of synthetic 3-D common-shot gathers are investigated and analyzed. Our goal is to constitute a practical procedure in a productive way that is capable of supporting the 3-D prestack seismic imaging for real 3-D surveys.

Introduction

The importance of imaging a complex 3-D structure using 3-D prestack depth migration has long been recognized by the petroleum industry. The implementation of the algorithm on large scale shared memory and distributed memory computers for real field data processing has been presented (Kao, 1992; Epili, 1995; Zhang, 1995). Nearly all procedures proposed in the previous publications are based on the Kirchhoff summation method in which the computing consists of two independent phases, the ray tracing and imaging construction. In the first step, traveltimes of ray paths from all surface grids to all depth points in the output 3-D volume are calculated and saved. The construction of 3-D imaging is realized by summing the samples from input traces to output grids based on the traveltime information.

The Kirchhoff summation method has become a standard scheme for the 3-D prestack depth migration due to its efficiency in computing and the amenability to irregular survey geometry. However, due to the limitation in the hardware configurations, some practical difficulties, such as the memory requirement, traveltime table storage and accessing, I/O bandwidth, speed of floating point operations, etc., still challenge the geophysical industry to make this method a routine procedure for 3-D seismic data processing.

An alternative of the prestack imaging procedure in the frequency domain has recently proposed by Huang and Wu (1996). The method constructs 3-D images by performing recursive downward extrapolation of wavefields using phase-screen propagators for each input common-shot gather. The method is motivated from the early work of the phase-shift migration method (Gazdag, 1978) and the split-step Fourier migration method (Stoffa, 1990). It takes into account lateral velocity variations as well as lateral density variations of 3-D heterogeneous media. Special efforts are devoted to the designing of an algorithm that uses much less memory allocation and computing time compared to finite-difference based migration methods, such as the reverse time migration (Chang and McMechan, 1990).

The prestack migration using phase-screen propagators is an imaging method based on the wave theory. It pertains several advantages that cannot be achieved by the ray-theory based Kirchhoff summation method. For example, it is an one-way wave propagation algorithm that can handle all forward scattering phenomena including focusing/defocusing, diffraction, interference and creeping waves. In principle, it offers higher image resolution than the ray-Kirchhoff summation method, which is limited by the Fresnel radius of ray tubes. The troublesome of computing and storing the huge traveltime table is entirely eliminated. The problems that the ray-Kirchhoff method encounters at complex geological environments such as caustics, multi-pathing and interferences can be avoided. However, the major drawback of the phase-screen extrapolation computing is that the floating operation is much more intensive than the Kirchhoff summation approach that makes the processing difficult to be realized on a conventional computing device for real 3-D field data.

The simultaneous execution of hundreds or thousands of processors in a computation is generally considered as the massively parallel computing. Massively parallel systems can run an application several orders of magnitude faster than most serial or vector computers. The Cray T3D MPP is a massively parallel computer with the processing elements (PEs) interconnected in a 3-D bidirectional torus which offers the

most efficient communication link among PEs. We implemented the phase-screen migration scheme on a 128PEs T3D MPP installed in Cray Research's headquarters in Eagan, Minnesota as this system provides fresh opportunities for developing efficient algorithm and programming solutions for 3-D prestack migration problems.

T3D MPP architecture

A Massively Parallel Processors (MPP) computer system contains hundreds or thousands of microprocessors, each accompanied by a local memory. Each microprocessor with its local memory component is called a processing element (PE).

The CRAY T3D MPP is a scalable heterogeneous computing system with multiple-instruction multi-data (MIMD) character in architecture. It is scalable from 16 to 1024 nodes with two processors in each node. The memory of T3D is physically distributed and is globally addressable by each PE. The interconnect network is a 3-D torus that was designed to minimize the network distance and provide highest known bisection bandwidth among PEs. Each processing element node contains two PEs, a network interface, and a block transfer engine.

Local memory consists of dynamic random access memory (DRAM) that stores system data. A low-latency, high-bandwidth data path connects the microprocessor to the local memory in a PE. The interconnect network provides communication paths among nodes and forms a three-dimensional matrix of paths that connect the nodes in three dimensions. The size of local memory is 8 Million words using 16-Mbit DRAM integrated circuits.

Methodology

The prestack depth migration scheme we used is based on a dual domain method using phase-screen propagators devised by Huang and Wu (1996). The principle and implementation procedure of the method can be summarized as follows. Under the phase-screen approximation, the downward extrapolation of acoustic wave fields in the dual domain representation can be written as (cf Wu and Huang, 1992, 1995; Huang and Wu, 1996)

$$P(\mathbf{K}_T, z_{i+1}) = e^{ik_z(z_{i+1}-z_{is})} \iint d^2\mathbf{x}_T e^{-i\mathbf{K}_T \cdot \mathbf{x}_T}$$
$$P_0(\mathbf{x}_T, z_{is})e^{ikS_v(\mathbf{x}_T, z_{is})} , \qquad (1)$$

where

$$S_v(\mathbf{x}_T, z_{is}) = \frac{1}{2} \int_{z_i}^{z_{i+1}} dz[\varepsilon_\kappa(\mathbf{x}_T, z) - \varepsilon_\rho(\mathbf{x}_T, z)] , \quad (2)$$

is the equivalent velocity screen of the thin-slab bounded between z_i and z_{i+1}. z_{is} is the average depth of the thin-slab. ε_κ is the bulk modulus perturbation function and ε_ρ is the density perturbation function. For the case of small depth step $\Delta z = z_{i+1} - z_i$ and constant density, the velocity screen can be further simplified as

$$S_v(\mathbf{x}_T, z_{is}) = \frac{1}{2}\Delta z \left[\frac{v_0^2(z_{is})}{v^2(\mathbf{x}_T, z_{is})} - 1 \right] , \qquad (3)$$

where $v(\mathbf{x}_T, z_{is})$ is the local velocity and $v_0(z_{is})$, the background velocity of the thin-slab. In equation (1), $P_0(\mathbf{x}_T, z_{is})$ is obtained from $P(\mathbf{x}_T, z_i)$ by a phase-shift extrapolation

$$P_0(\mathbf{x}_T, z_{is}) = \frac{1}{4\pi^2} \iint P(\mathbf{K}_T, z_i)e^{ik_z(z_{is}-z_i)}$$
$$e^{i\mathbf{K}_T \cdot \mathbf{x}_T} d^2\mathbf{K}_T . \qquad (4)$$

Taking the inverse Fourier transform of $P(\mathbf{K}_T, z_{i+1})$ over $\mathbf{K}_T$, the downward propagating wave field at depth z_{i+1} is extrapolated from the wave field at depth z_i. This procedure of dual domain shuttling is implemented recursively for downward extrapolation. The complex-conjugate extrapolator of (1) is used for the backpropagation of wave fields from common-shot gathers. A frequency domain imaging condition is used (cf Huang and Wu, 1996).

Implementation

The processing of the wavefield extrapolation is inherently parallel in the frequency domain. It is, therefore, natural to implement the algorithm in a way that a frequency slice of surface wavefields is processed within a single PE.

Initially, a three-dimensional velocity screen function is calculated using equation (3). Two 3-D arrays of same size need to be allocated to store the velocity screen function and the output 3-D migrated imaging. For general 3-D survey, the required memory could be in a order of several gigabytes. These two 3-D arrays are evenly partitioned and distributed over the local memories of all available PEs. With the local memory size of eight million words in each PE, this allocation should not cause a substantial problem on a T3D MPP.

Our method of implementing the scheme is that the input time domain data are first sorted into common shot gather and transformed into the frequency domain. Only interested frequency components are saved and distributed to the local memories of available PEs.

The computation is recursive in depth but parallel in frequency slices. The only communication during the wavefield extrapolation steps is to fetch the velocity screen data at a specific depth from a remote

PE. The depth levels can be grouped into thicker layers to lessen the communication burden. Although the higher frequency component requires a little more computation time, the overall computation are pretty balanced during the extrapolation within the depth loop. We can clearly see that no synchronization barrier is needed to block the computing until to the end of the depth loop. At that point a global-sum step is executed to add partial images from all frequency slices to construct the migrated output from a single shot gather input. All shot gathers are processed and superimposed to form the final 3-D output volume.

The algorithm can be summarized as follows:

- *Generate the velocity screen functions for all depth levels. Partition and distribute this 3-D data array to local memories of all available PEs.*

- *For all common shot gathers*

  - *FFT input traces from the time domain to the frequency domain.*
  - *Move frequency slices into local memories of PEs.*
  - *2D FFT frequency slices from the space domain to the wavenumber domain.*
  - *For all depth levels*
    * *Fetch the velocity screen function at a depth level.*
    * *Construct propagators and downward extrapolate the wavefields from a source and receivers to the next depth level.*
    * *2D inverse FFT the wavefields to the space domain.*
    * *Interact with the velocity screen function.*
    * *Apply the imaging condition.*
    * *2D FFT the wavefields to wavenumber domain.*
  - *End of the depth level loop*
  - *Global-sum migrated outputs from all PEs and superimpose the results to the 3D migrated volume.*

- *End of the shot loop*

It is noted that each PE owns one frequency slice in its local memory and all PEs perform wavefield downward extrapolation in parallel.

Performance

One of the key factors in improving the efficiency of the migration scheme is to minimize the communication overhead. The rate of data moving between PEs has been addressed (Numrich, 1994). Our experiments indicate that a significant percent of total processing time is used by the data communication.

Complex 2D FFT operations are the heart of the scheme. It consumed a majority of total processing time. An optimized 2D Complex FFT subroutine in the Cray T3D library was utilized to speed up the computation. This subroutine has the capability of spreading the FFT work over several PEs. Therefore, the algorithm can be further parallelized on a larger MPP system.

In the numerical experiment, 60 frequency components are processed over a 128 PEs T3D. The work of 2D complex FFT process for each frequency slice is shared by 2 PEs. On a 3-D model of $N_x = N_y = 256$ and $N_z = 400$, the processing time in second and the percentages of time in 2D FFT and data moving executions are tabulated in Table 1.

$N_x \times N_y$	Data Move	2D FFT	Total time
(256×256)	4.42	52.86	62.18
percentage	7.11	85.01	100.00

Table 1. Processing times in second and work percentages for downward extrapolation of a common shot gather with 60 frequency components in a 3-D model ($256 \times 256 \times 400$).

In the second experiment, the same experiment was carried out to migrate a common shot gather for 400 depth levels in a 3-D model ($512 \times 512 \times 400$). The timing is tabulated in Table 2.

$N_x \times N_y$	Data Move	2D FFT	Total time
(512×512)	16.22	294.4	315.38
percentage	5.14	93.37	100.00

Table 2. Processing times in second and work percentages for downward extrapolation of a common shot gather with 60 frequency components in a 3-D model ($512 \times 512 \times 400$).

Conclusions

The 3-D prestack migration using phase-screen propagators is an efficient and stable scheme. The advent of MPP systems has encouraged the design of an algorithm for faster and more accurate 3-D prestack migration processing. We proposed a scalable, massively parallel algorithm for implementing the scheme on a T3D MPP system. A variety of optimizations has been applied to achieve the high processing speed. Our expectation is to design a practical scheme capable of implementing the prestack depth migration for real 3-D seismic surveys.

Our preliminary experiments of parallelizing the prestack phase-screen migration algorithm on the T3D MPP yield very promising results. However, many optimization techniques in T3D can be utilized to further speed up the computing. Moreover, due to the scalability nature of distributed memory system, the performance can certainly be improved on a MPP system with more PEs.

The proposed parallel distributive algorithm can be easily mapped onto different parallel architectures, where the hardware configurations are suited for the phase-screen migration scheme. The future work includes the actual implementing and benchmarking of the proposed algorithm in a productive way for real 3-D field data.

Acknowledgements

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